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Investigating The Impact Of Diethyl Ether (DEE) Additive On The Performance And Emission Characteristics Of A Common Rail Direct Injection (CRDI) Diesel Engine Utilizing Diesel And Cotton Seed Oil Blends

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The rising concern for environmental sustainability and the depletion of fossil fuel reserves have accelerated the search for alternative fuels that can provide efficient combustion with reduced emissions. This study investigates the impact of Diethyl Ether (DEE) as an additive on the performance and emission characteristics of a Common Rail Direct Injection (CRDI) diesel engine using various blends of diesel and cottonseed oil (CSO). The test fuels include Pure Diesel (PD), a blend of 20% cottonseed oil and 80% diesel (CSO20D80), and DEE-enriched blends of CSO20D80 with 5%, 10%, and 15% DEE concentrations. The experimental analysis was conducted at varying engine loads to evaluate brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), exhaust gas temperature (EGT), and exhaust emissions such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and smoke opacity. The results indicate that the addition of DEE improves the combustion characteristics of CSO20D80, enhancing BTE and reducing BSFC at higher loads, particularly with the CSO20D80+15% DEE blend. Emission analysis revealed that while NOx emissions increase with higher DEE content, significant reductions in CO, HC, and smoke opacity are observed, demonstrating the cleaner combustion nature of DEE. Notably, the CSO20D80+15% DEE blend exhibited the best overall performance and emission profile among the tested fuels, making it a viable and sustainable alternative to pure diesel for CRDI engines. This study emphasizes the potential of DEE-enriched biodiesel blends in reducing reliance on fossil fuels while enhancing engine efficiency and environmental performance.

Key words: CRDI Diesel engine, Cotton Seed Oil, DEE, Performance, emissions.

Introduction:

The exploration of alternative fuels for diesel engines is driven by the need to address environmental concerns and the diminishing availability of petroleum-based fuels. Biodiesel, a renewable and environmentally friendly alternative, is derived from organic materials such as vegetable oils, animal fats, and waste cooking oils through transesterification, making it compatible with existing diesel engines without significant modifications [1]. Biodiesel offers significant environmental benefits, including reduced greenhouse gas emissions and improved air quality due to lower sulfur oxides and particulate matter emissions [2]. However, challenges such as feedstock competition with food crops and energy balance concerns remain [3]. Studies have shown that using biodiesel can lead to a reduction in nitrogen dioxide and soot emissions, although it may result in increased fuel consumption and decreased engine power due to poorer mixture quality [4]. To enhance performance and meet emission standards, biodiesel can be blended with additives like diethyl ether and used with exhaust gas recirculation (EGR) systems, which have been shown to significantly reduce NO emissions while slightly decreasing engine torque [5]. Additionally, renewable diesel, produced through hydrodeoxygenation of lipid feed stocks, offers a composition similar to petroleum diesel and is being explored alongside biodiesel as a viable alternative [6]. Other alternative fuels, such as methane and natural gas, are also being considered due to their low cost and potential to improve engine efficiency, although they may increase NOx emissions [7]. The use of blends, such as those combining diesel, biodiesel, and ethanol, has been analyzed for their thermodynamic, economic, and environmental impacts, showing that while commercial diesel outperforms in thermal efficiency, biodiesel blends offer lower environmental costs [8]. Furthermore, innovative approaches like using aloevera biodiesel and powder have demonstrated reduced NOx emissions and improved combustion characteristics, albeit with some performance trade-offs [9]. The maritime sector is also transitioning towards low and zero-emission fuels, such as LNG and methanol, to meet stringent emission regulations, highlighting the broader applicability of alternative fuels beyond road transportation [10]. The integration of alternative fuels into diesel engines is crucial for reducing emissions and enhancing energy security, with ongoing research focusing on optimizing production processes and exploring new feedstocks to overcome existing challenges[6]. Overall, the shift towards alternative fuels in diesel engines represents a significant step towards a more sustainable energy landscape, offering environmental, economic, and societal benefits while reducing dependence on fossil fuels.

Diethyl ether (DEE) is increasingly being explored as an additive in diesel engine alternative fuels due to its potential to enhance performance and reduce emissions. DEE is an oxygenated compound that can improve combustion efficiency and reduce harmful emissions when blended with biodiesel or diesel. Studies have shown that DEE, when added to biodiesel blends such as waste cooking oil methyl ester (WCOME), can improve brake thermal efficiency (BTE) and reduce emissions like nitrogen oxides (NOx) and hydrocarbons (HC) at full load conditions. For instance, a blend of 20% WCOME with 5% DEE (B20DEE5) demonstrated a slight increase in BTE and a significant reduction in NOx and HC emissions compared to pure diesel [11]. Similarly, DEE has been used with Karanja methyl ester (KME) biodiesel blends, where it was found to decrease brake specific fuel consumption (BSFC) and increase BTE, while also reducing emissions such as NOx, CO, and smoke [12]. DEE's high cetane number and low auto-ignition temperature make it a suitable additive for compression ignition engines, potentially reducing urban air pollution by lowering NOx, SOx, and particulate matter emissions [13]. However, the use of DEE requires careful consideration of its physical properties, such as lower viscosity and lubricity, which may necessitate modifications to engine components [14]. In addition to biodiesel blends, DEE has been combined with ethanol in diesel engines to improve combustion and emissions characteristics. For example, adding DEE to an ethanol-diesel blend (D-E10) improved smoke and NOx emissions, with an optimal DEE addition of 8% resulting in the lowest NOx emissions and highest BTE at full load [15]. Furthermore, DEE's role in reducing NOx emissions has been highlighted in various studies, where it was found to lower flame temperatures due to its high latent heat of vaporization, thus reducing NOx emissions at lower loads [16]. The low-temperature oxidation behavior of DEE also plays a crucial role in its effectiveness as a fuel additive, as it influences the combustion process and emissions profile [17]. Additionally, DEE has been used in combination with other additives, such as ethanol and butanol, to further enhance diesel engine performance and reduce emissions. For instance, a hybrid additive approach using ethanol, butanol, and magnetite nanoparticles showed significant improvements in BTE and reductions in emissions like HC, CO, and NOx when used with biodiesel blends [18]. Overall, DEE's potential as an additive in diesel engine alternative fuels is promising, offering a feasible solution to improve engine performance and reduce emissions, although further research and development are needed to optimize its use and address any technical challenges [19].

2. Materials and Methods

2.1. Preparation of Cotton Seed Oil Blends

The preparation of cotton seed oil blends involves combining specific proportions of cotton seed oil (CSO) with conventional diesel (D) fuel to create biofuel blends suitable for use in diesel engines. Blending cotton seed oil with diesel improves fuel properties such as viscosity and combustion characteristics, making it more suitable for engine applications. Table 1 represents the properties of the various test fuels.

Figure 1: Preparation of Cotton Seed Oil

Table 1: Properties of DEE blends

Property	**ASTM Standard**	**Pure Diesel**	**CSO20D 80**	**CSO20D 80+ 5%DEE**	**CSO20D 80+ 10%DEE**	**CSO20D 80+ 15%DEE**
Density @ 15°C in (g/cc)	ASTM D4052	840	860	855	850	845
Gross calorific value (MJ/kg)	ASTM D4052	42.5	41.3	41.1	40.8	40.5
Kinematic viscosity, cst @ 40°C	ASTM D4052	2.8	3.8	3.6	3.4	3.2
Cetane number	ASTM D4052	55	48	52	54	56
Flash point (°C)	ASTM D4052	80	110	95	90	85
Oxygen Conten(%)	ASTM D4052	0	2	3	4	5

2.2. Experimental Setup

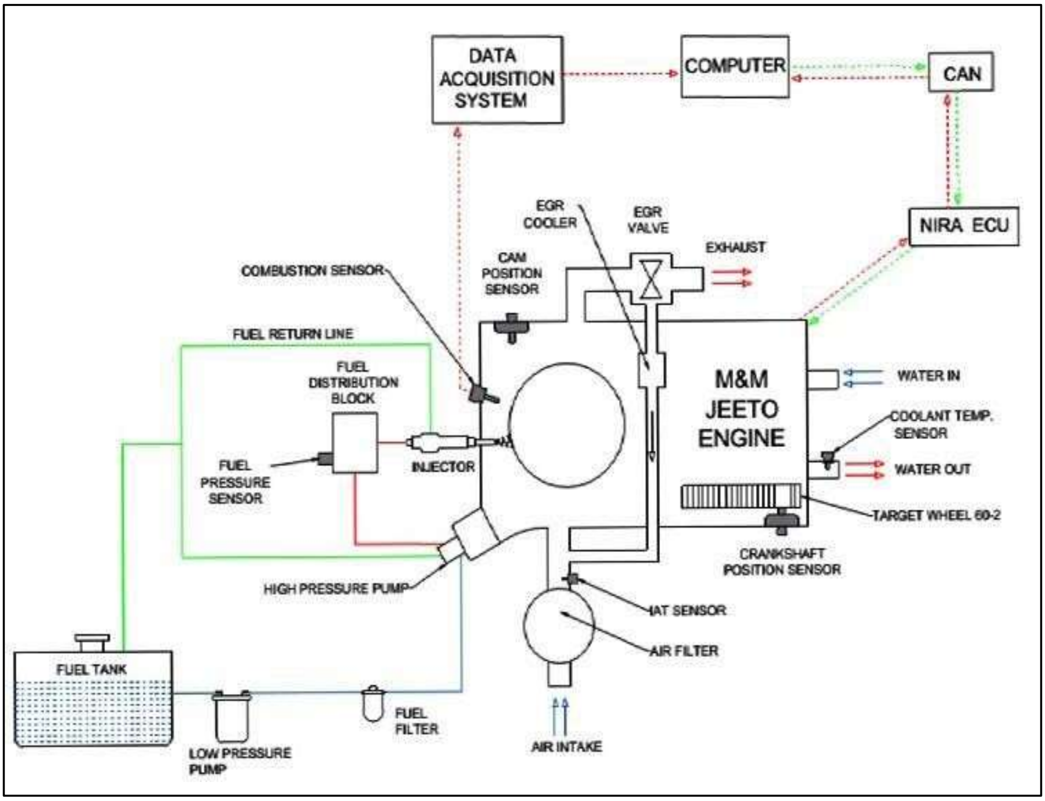

Figure 2: Schematic diagram of experimental set up

The experiment employed a Mahindra JEETO automotive research engine as the primary testing platform. This engine, which is schematically presented in Figure 2 and comprehensively detailed in Table 2, is a single-cylinder, four-stroke, dual-fuel diesel engine specifically designed for research applications. The engine is equipped with a water-cooling system that ensures the engine operates efficiently by maintaining stable temperature conditions, even during extended testing sessions. An open Engine Control Unit (ECU) is integrated into the setup to perform a range of critical functions. This ECU is responsible for monitoring and interpreting sensor data, accurately calculating the fuel mass required for efficient combustion, and controlling the injection timing and fuel pressure, which can be regulated up to 1000 bar. Additionally, it ensures engine synchronization by identifying the Top Dead Center (TDC), manages the main relay for system operations, and regulates engine speed for precise control during testing. Communication capabilities are also embedded within the ECU to facilitate data exchange. The calibration of the ECU is conducted through PC-based software, which serves a dual purpose: it enables the configuration and fine-tuning of the ECU parameters and logs all relevant engine data in real-time during operations. This allows for continuous monitoring and analysis of engine performance under varying conditions. The specific model of the open ECU utilized is the MCS1-i7, which is connected to the data acquisition system using a Kvaser Leaf Light V2 CAN cable. This configuration ensures efficient data transmission and enables the accurate recording and analysis of engine behavior, providing valuable insights throughout the experiment

2.3. Fabrication of combustion chamber of LHR Engine

Figure 3: Photographic view of the ceramic coated cylinder head

Figure 3 represents the fabrication of the combustion chamber for the Low Heat Rejection (LHR) engine involved a specialized coating process aimed at enhancing thermal efficiency and reducing heat loss. To achieve this, the inner surface of the cylinder head was coated with a layer of partially stabilized zirconium (PSZ). This material is known for its high thermal resistance and durability, making it an ideal choice for insulating components exposed to extreme temperatures within the combustion chamber. The coating process employed was plasma spraying, a technique that allows for precise and uniform application of the coating material. Plasma spraying involves the generation of a high-temperature plasma jet, which is used to melt the PSZ powder before spraying it onto the target surface. In this case, a 500-micron thick layer of PSZ was applied to the inner portion of the cylinder head. This thickness was carefully selected to provide optimal thermal insulation while maintaining the structural integrity of the component. By applying the PSZ coating, the combustion chamber becomes more efficient in retaining heat, reducing the amount of heat lost to the surrounding components. This enhancement improves the overall thermal efficiency of the engine, allowing for higher combustion temperatures, which in turn can lead to improved fuel efficiency and performance. The use of partially stabilized zirconium also helps to enhance the longevity of the cylinder head by providing a protective barrier against the high thermal stress and chemical reactions occurring during combustion.

Table 2: Specifications of the test engine

Description	**Specification**
Make	Mahindra & Mahindra
Number of cylinders	01
Number of Strokes	04
Ratio of bore to stroke	93 mm/92 mm
Power	6.6 kW (9 HP) at the rated speed of 3000rpm
Compression Ratio	18:1
Type of cooling Arrangement	Water cooling
Recommended Injection Pressure	190 bar
Recommended Injection Timing	27 degrees before top dead center
Maximum Torque	30 Nm at 1800 rpm.

Table 3: Range and accuracy of Analyzers

S.No	Name of the Analyzer	Principle Adopted	Range	Accuracy
1	AVLSmoke Analyzer	Opacity	0-100 HSU (Hartridge Smoke unit)	±1 HSU
2	Netel Chromatograph CO analyzer	Infrared absorption spectrograph	0-10%	± 0.1%

3	Netel Chromatograph UBHC analyzer	NDIR	0-1000 ppm	±5 ppm
4	Netel Chromatograph NO_x analyzer	Chemiluminiscence	0-5000pm	±5 ppm

3. Results and Discussions

3.1. Brake Thermal Efficiency

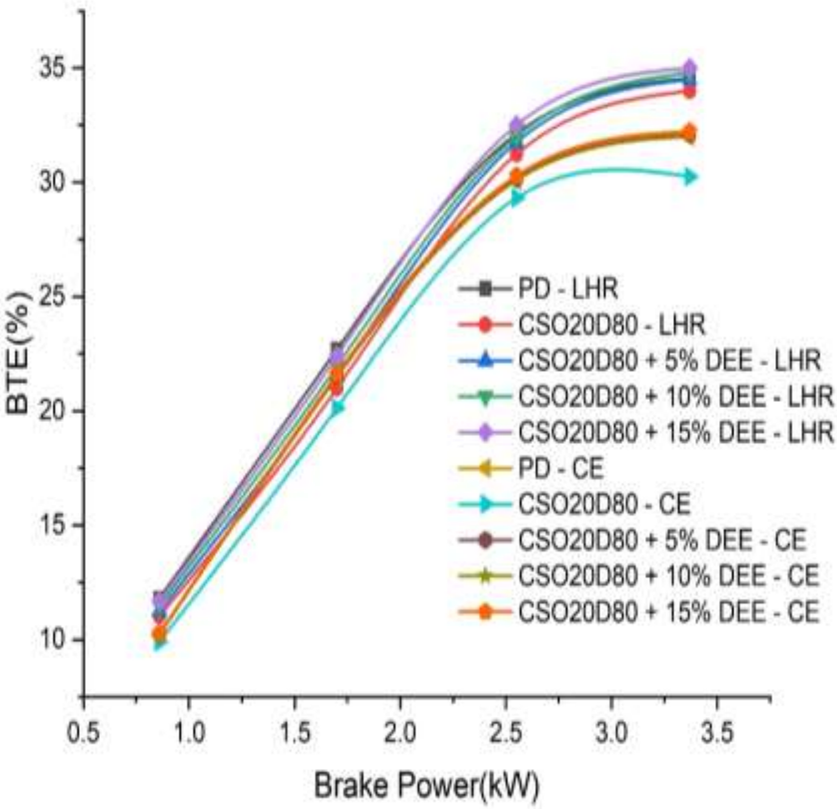

Figure 4. BP vs BTE with different versions of the engine

The figure 4 illustrates the Brake Thermal Efficiency (BTE) versus Brake Power (BP) for both Low Heat Rejection (LHR) and Conventional Engines (CE) using various fuel blends, including pure diesel (PD), CSO20D80 (20% Cotton Seed Oil + 80% Diesel), and CSO20D80 with different percentages of Diethyl Ether (DEE). In LHR engines, the addition of DEE to the CSO20D80 blend results in a noticeable increase in BTE, especially at higher brake power, due to the improved combustion process facilitated by the retention of heat within the engine. The highest BTE is observed with the CSO20D80 + 15% DEE blend in the LHR engine, highlighting the benefits of the oxygenated DEE additive in enhancing fuel efficiency. Conversely, the lowest BTE is recorded for the CSO20D80 blend in the conventional engine, likely due to the higher viscosity and lower volatility of the blend, leading to less efficient combustion. Overall, while the addition of DEE improves BTE in both engine types, the effect is more pronounced in LHR engines, where the design better capitalizes on the improved combustion characteristics provided by DEE.

3.2 Brake Specific Fuel Consumption

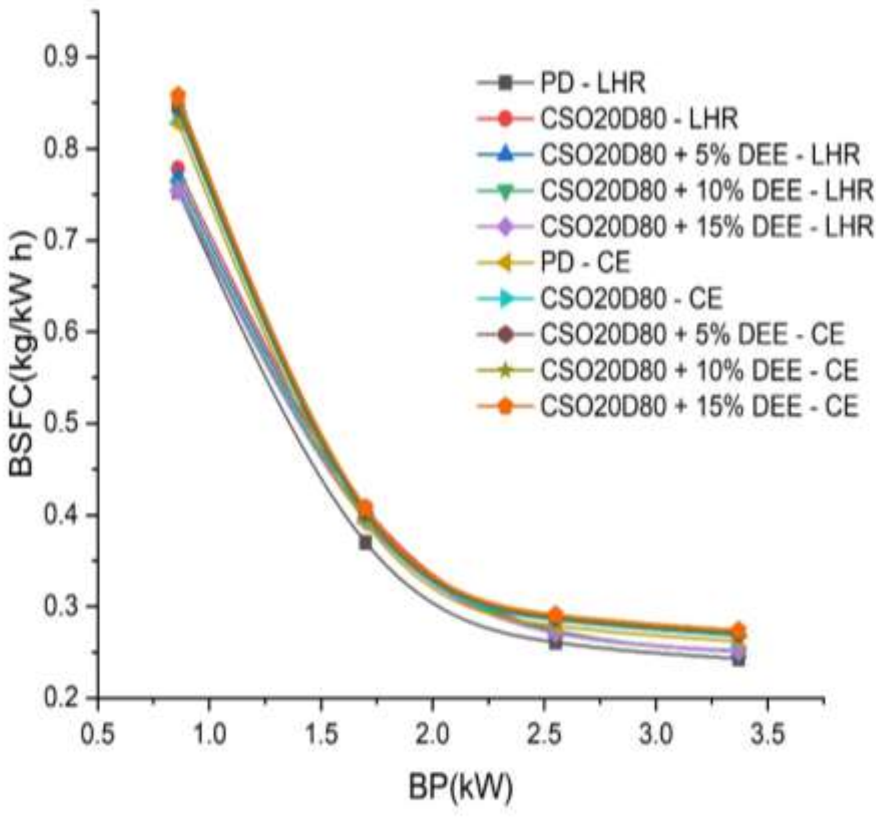

Figure 5. BP vs BSFC with different versions of the engine

The graph 5 depicts the relationship between Brake Specific Fuel Consumption (BSFC) and Brake Power (BP) for both Low Heat Rejection (LHR) and Conventional Engines (CE) using various fuel blends, including pure diesel (PD), CSO20D80 (20% Cotton Seed Oil + 80% Diesel), and CSO20D80 with different percentages of Diethyl Ether (DEE). Across both engine types, the BSFC decreases as brake power increases, indicating more efficient fuel usage at higher loads. Notably, the LHR engine consistently exhibits lower BSFC values compared to the conventional engine, reflecting its higher thermal efficiency due to reduced heat loss. Among the different blends, the CSO20D80 + 15% DEE combination in the LHR engine shows the lowest BSFC, highlighting its superior fuel efficiency. In contrast, the CSO20D80 blend in the conventional engine generally has the highest BSFC, particularly at lower brake power, due to less complete combustion and higher heat rejection. The addition of DEE in both engines improves fuel efficiency, with the effect being more pronounced in the LHR engine, demonstrating the effectiveness of DEE in enhancing combustion and reducing fuel consumption.

3.3 Exhaust Gas Temperature

Figure 6 shows the relationship between Exhaust Gas Temperature (EGT) and Brake Power (BP) for both Low Heat Rejection (LHR) and Conventional Engines (CE) using various fuel blends, including pure diesel (PD), CSO20D80 (20% Cotton Seed Oil + 80% Diesel), and CSO20D80 with different percentages of Diethyl Ether (DEE). As brake power increases, the EGT also rises across all fuel blends and engine types, indicating higher combustion temperatures at higher loads. The LHR engine generally exhibits higher EGTs compared to the conventional engine, which is expected due to its design that retains more heat within the combustion chamber, leading to more complete combustion and higher exhaust temperatures. Among the different blends, the CSO20D80 + 15% DEE in the LHR engine shows the highest EGT, reflecting the enhanced combustion efficiency with the addition of DEE. In contrast, the PD-CE combination tends to have the lowest EGTs, particularly at higher brake powers, likely due to more heat being lost in the conventional engine design. The addition of DEE across both engines increases the EGT, with a more significant impact observed in the LHR engine, suggesting improved combustion quality and energy release with DEE, leading to higher exhaust temperatures.

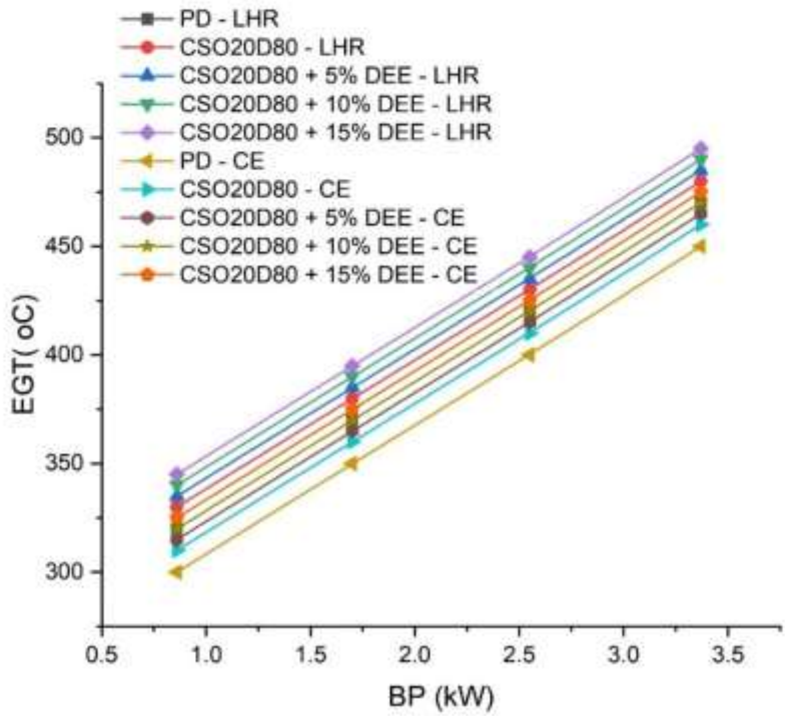

Figure 6. BP vs EGT with different versions of the engine

3.4 CO Emissions

The Figure 7 illustrates the relationship between Carbon Monoxide (CO) emissions (as a percentage of volume) and Brake Power (BP) for both Low Heat Rejection (LHR) and Conventional Engines (CE) using various fuel blends, including pure diesel (PD), CSO20D80 (20% Cotton Seed Oil + 80% Diesel), and CSO20D80 with different percentages of Diethyl Ether (DEE). As brake power increases, CO emissions generally decrease across all fuel blends and engine types, indicating more complete combustion at higher loads. The LHR engine consistently produces lower CO emissions compared to the conventional engine, which can be attributed to its design that enhances combustion efficiency by retaining more heat. Among the different blends, the CSO20D80 + 15% DEE in the LHR engine shows the lowest CO emissions, suggesting that the addition of DEE significantly improves the combustion process, reducing the production of CO. In contrast, the PD-CE combination has the highest CO emissions, particularly at lower brake powers, due to less efficient combustion in the conventional engine. The addition of DEE reduces CO emissions in both engine types, with a more pronounced effect in the LHR engine, further emphasizing the role of DEE in enhancing combustion quality and reducing incomplete combustion by-products like CO.

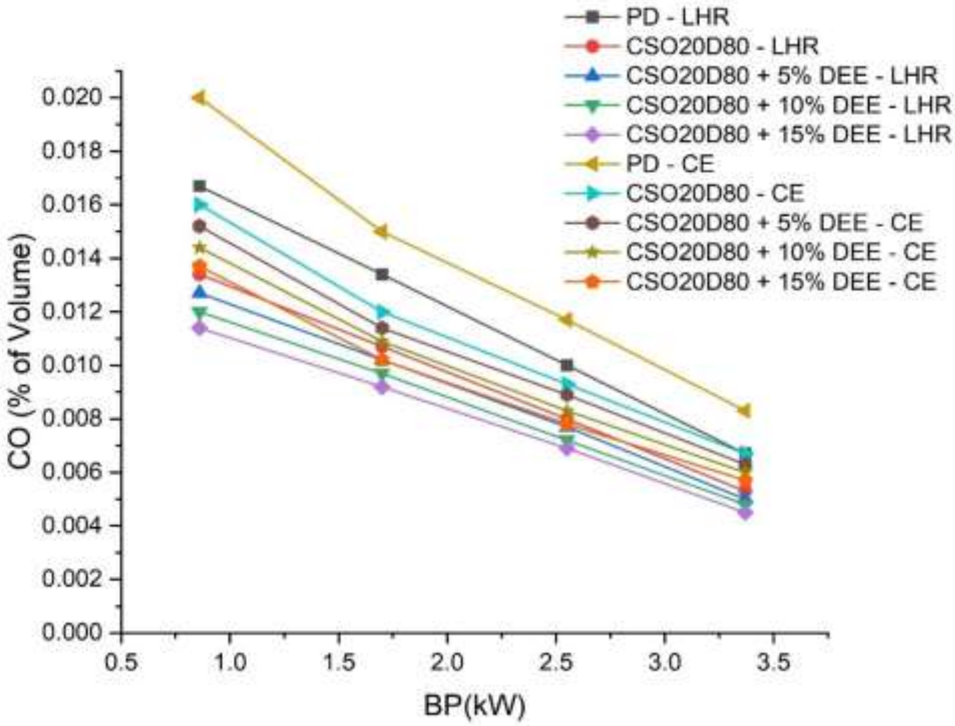

Figure 7. BP vs CO emissions with different versions of the engine

3.5 HC Emissions

The figure 8 depicts the relationship between Hydrocarbon (HC) emissions (measured in ppm) and Brake Power (BP) for both Low Heat Rejection (LHR) and Conventional Engines (CE) using various fuel blends, including pure diesel (PD), CSO20D80 (20% Cotton Seed Oil + 80% Diesel), and CSO20D80 with different percentages of Diethyl Ether (DEE). As brake power increases, HC emissions decrease across all fuel blends and engine types, indicating more complete combustion at higher loads. The LHR engine consistently shows lower HC emissions compared to the conventional engine, reflecting its superior combustion efficiency due to its ability to retain more heat and reduce incomplete combustion. Among the different blends, the CSO20D80 + 15% DEE in the LHR engine exhibits the lowest HC emissions, underscoring the positive impact of DEE in enhancing the combustion process and reducing unburned hydrocarbons. Conversely, the PD-LHR combination produces the highest HC emissions, particularly at lower brake powers, likely due to the less effective combustion of pure diesel in the LHR engine without the benefits of DEE. The addition of DEE to the fuel blends reduces HC emissions in both engine types, with the most significant reduction observed in the LHR engine, highlighting DEE's role in improving combustion efficiency and reducing emissions.

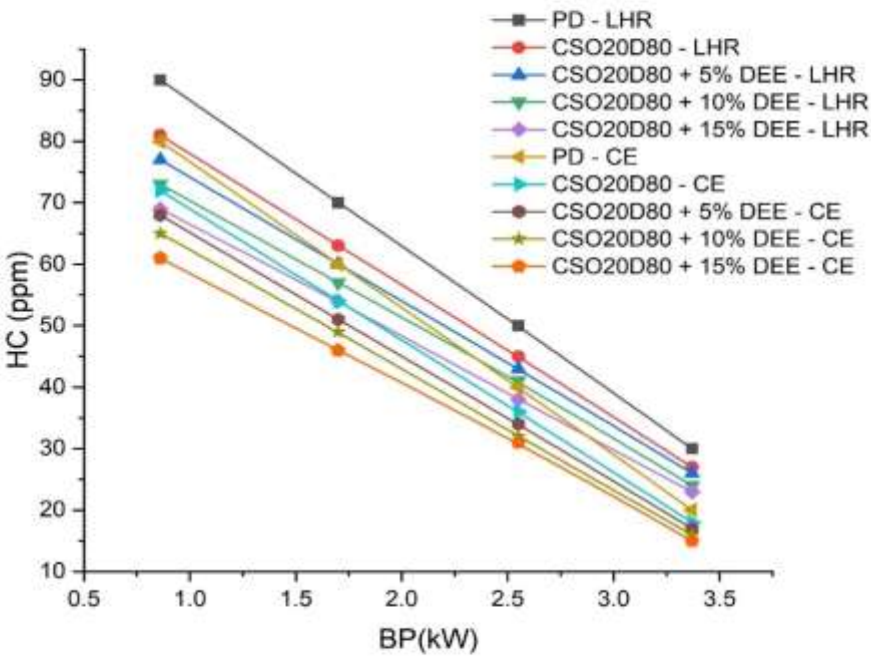

Figure 8. BP vs HC emissions with different versions of the engine

3.6 Smoke emissions

The graph 9 illustrates the relationship between Smoke Opacity (measured as a percentage of opacity) and Brake Power (BP) for both Low Heat Rejection (LHR) and Conventional Engines (CE) using various fuel blends, including pure diesel (PD), CSO20D80 (20% Cotton Seed Oil + 80% Diesel), and CSO20D80 with different percentages of Diethyl Ether (DEE). As brake power increases, smoke opacity decreases across all fuel blends and engine types, indicating more efficient combustion with less soot formation at higher loads. The LHR engine generally produces lower smoke opacity compared to the conventional engine, highlighting its improved combustion efficiency due to better heat retention, which helps in more complete fuel burning. Among the different blends, the CSO20D80 + 15% DEE in the LHR engine shows the lowest smoke opacity, demonstrating the significant impact of DEE in reducing smoke emissions by enhancing the combustion process. In contrast, the PD-LHR combination has the highest smoke opacity, particularly at lower brake powers, likely due to incomplete combustion of pure diesel in the LHR engine without the additional oxygen provided by DEE. The addition of DEE to the fuel blends consistently reduces smoke emissions in both engine types, with the most notable reduction seen in the LHR engine, underscoring DEE's effectiveness in lowering soot production and improving overall emission quality.

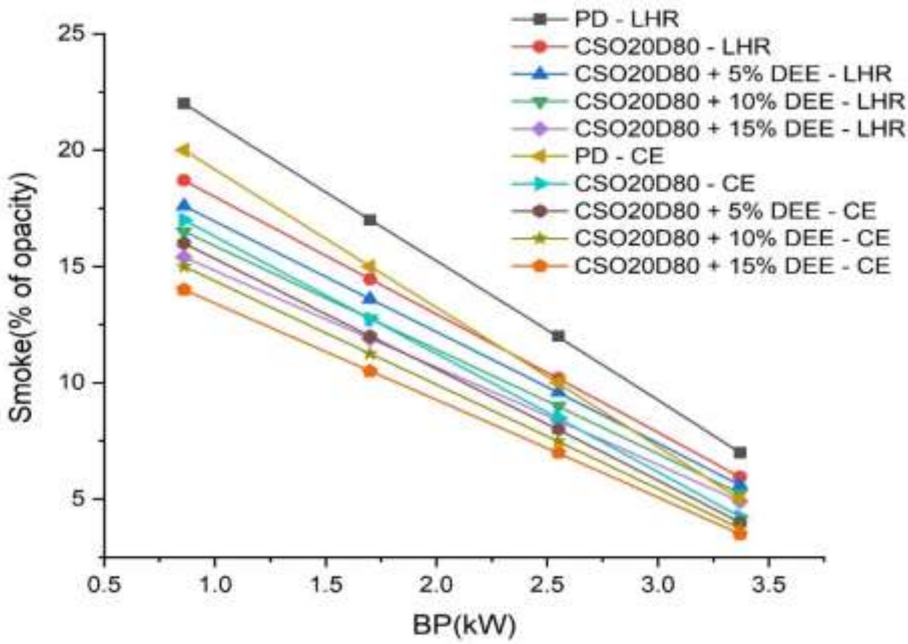

Figure 9. BP vs HC emissions with different versions of the engine

4. Conclusions:

This study evaluates the impact of Diethyl Ether (DEE) as an additive on the performance and emission characteristics of a Common Rail Direct Injection (CRDI) diesel engine using diesel and cottonseed oil (CSO) blends. Based on the experimental analysis, the following conclusions were drawn:

Performance Improvements:

The addition of DEE to the CSO20D80 blend significantly enhances the Brake Thermal Efficiency (BTE) of the engine, particularly at higher brake power. This improvement is more pronounced in Low Heat Rejection (LHR) engines, which effectively retain heat and optimize combustion.

Brake Specific Fuel Consumption (BSFC) is reduced with the addition of DEE, with the CSO20D80+15% DEE blend exhibiting the lowest BSFC in both engine types, highlighting its efficiency advantage.

Emission Reductions:

DEE addition results in reduced emissions of carbon monoxide (CO), hydrocarbons (HC), and smoke opacity across both LHR and conventional engines. The CSO20D80+15% DEE blend consistently showed the lowest emissions, making it the most efficient in terms of clean combustion.

Nitrogen oxide (NOx) emissions, however, tend to increase with higher DEE concentrations. This is attributed to the higher combustion temperatures facilitated by the oxygenated nature of DEE, which supports a more complete combustion process but also raises flame temperatures.

Optimized Blend:

Among all tested fuel blends, CSO20D80+15% DEE proved to be the most effective, demonstrating superior performance in terms of both efficiency and emissions. This blend offers a viable and sustainable alternative to pure diesel, especially for LHR engine configurations.

Potential for Sustainability:

The results indicate that DEE-enriched CSO blends can effectively reduce dependence on pure diesel while enhancing engine performance and reducing harmful emissions. This highlights the potential for DEE as a promising additive for biodiesel blends, promoting sustainability in diesel engine applications.

Disclosure of Interest

We have no conflict of Interest

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